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Physics Beyond the Standard Model and Cosmological Connections: A Summary from LCWS 06

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Abstract. The International Linear Collider (ILC) is likely to provide us important insights into the sector of physics that may supersede our current paradigm viz., the Standard Model. In anticipation of the possibility that the ILC may come up in the middle of the next decade, several groups are vigourously investigating its potential to explore this new sector of physics. The Linear Collider Workshop in Bangalore (LCWS06) had several presentations of such studies which looked at supersymmetry, extra dimensions and other exotic possibilities which the ILC may help us discover or understand. Some papers also looked at the understanding of cosmology that may emerge from studies at the ILC. This paper summarises these presentations.

Keywords. Beyond Standard Model Physics, Collider Physics, Cosmological Connections

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1. Introduction

For several years, there has been a wide-spread realisation in the High Energy Physics community of the importance of a high-energy linear collider to study TeV-scale physics in the scattering of electrons, positrons and photons. This realisation has found concrete articulation in a project now known as the International Linear Collider (ILC) [1–6]. Due to the nature of the leptonic and photonic initial states, such a collider will provide a very clean environment setting the stage for the probing the TeV scale with remarkably high precision. Much in the same way as the LEP experiments in CERN complemented the UA1 and UA2 experiments in understanding the gauge sector of the Standard Model (SM), the ILC is expected to complement the Large Hadron Collider (LHC) in the quest to understand the nature of electroweak symmetry breaking and its ramifications [7].

Moreover, compelling theoretical arguments tell us that electroweak symmetry-breaking also holds the key to the discovery of new physics: the much sought-after 'physics beyond the Standard Model'. From a purely phenomenological point of view, almost any kind of new physics can be expected at the high energies that these colliders will probe. But high-energy theorists have focussed their research on the sub-class of models which are consistent with some of the following principles: symmetry, renormalizability, unitarity, naturalness etc. To these principles are added consistency with existing experimental data and also accessibility of the theoretical models in upcoming experiments. These guiding principles narrow down the field considerably and the viable models that result fall into a few distinct classes.

Supersymmetry, or more precisely, the supersymmetric extension of the Standard Model is the most popular of these classes of models [8,9]. Indeed, the supersymmetric extension of the Standard Model is in no way unique but yields a whole class of models. Further simplifying assumptions, some based on aesthetic considerations and some decidedly ugly but simplifying nonetheless, are then added to arrive at a few models which have been the subjects of vigourous investigations. One of the major physics goals of the ILC will be a systematic investigation of various regions of the supersymmetric parameter space in a quest to understand the mechanism responsible for supersymmetry breaking [3].

Another class of models that has been studied as possible extensions of the SM are models based on the idea of Technicolour. While the minimal versions of these models are constrained by precision electroweak data, the non-minimal versions do manage to survive all existing constraints [10]. Indeed, in recent years, there has been a resurgence of interest in these models with the realisation that they can be thought of as being dual to some TeV scale extra-dimensional models [11]. Models of TeV-scale extra dimensions have opened up new avenues for theoretical speculation in high-energy physics [14,15]. These models provide new solutions to the hierarchy problem and predict a whole host of model-dependent experimental signatures at the TeV scale [16,17]. While the ILC may not be a discovery machine for this class of models, it will definitely help in pinning down the specifics of a model by providing a window within which to investigate the details of these models [18].

A major part of the preparation for the ILC involve theoretical studies and simulations of the physics that can be potentially studied at this collider [12,13]. Work has been carried out for several years now by individual researchers as well as dedicated working groups and this work includes several investigations of supersymmetry, extra dimensions, technicolor and other extensions of the SM. More recently, there has been considerable progress made in understanding the interplay between collider physics and cosmology and how collider searches for dark matter candidates in supersymmetry and other models can lead us to a determination of dark matter parameters and how this precision information may influence cosmology. This paper presents a summary of the work on Beyond Standard Model Physics and Cosmological Connections presented at the Linear Collider Workshop 2006 (LCWS06) [1].

2. Supersymmetry and the ILC

One of the major advantages of the ILC is that it will allow several precision studies of TeV-scale supersymmetry, help determine masses, branching ratios and supersymmetric parameters to a degree of accuracy that may help pinpoint the underlying mechanism of supersymmetry breaking.

A fundamental relation in SUSY is that between the gauge and the Yukawa coupling:

[1] The summary of Higgs physics, top physics, QCD studies and loop calculations can be found in Ref. [19].

$$\text{Gauge coupling } g = \text{Yukawa coupling } \hat{g} \quad (1)$$

Testing these relations via precise cross-section measurements is very important and a detailed study of how to measure these couplings at a Linear Collider was presented [20]. For example, selectron production at ILC and their decays into neutralinos can be studied and polarisation allows us to disentangle SU(2) and U(1) couplings and provides a measurement of these couplings to better than 1%. Things are more complicated with SU(3) at ILC because to produce coloured states one needs reactions like $e^+e^- \to \tilde{q}\tilde{q}g$. These rates turn out to be tiny unless the ILC operates at its highest planned centre-of-mass energy of 2 TeV.

The alternative is to do a combined LHC/ILC analysis and study production of squarks and their decays through charginos at the LHC and input values of squark and chargino/neutralino BRs measured precisely at the ILC. This method gives a test of the strong coupling identity down to a 4% level.

Precision electroweak data do not yield as sensitive an estimate of supersymmetric particle masses as they did for the top quark or the Higgs boson because decoupling guarantees that low-energy observables are insenstive to the effects of supersymmetric particles. On the other hand, loop processes involving supersymmetric particles may still be useful if the processes are either rare or forbidden in the SM. In the workshop, a detailed analysis of supersymmetric models was presented [21]. This analysis has been carried out using the precision measurements of electroweak observables like m_t, M_W and $\sin^2\theta_{\rm eff}$ from LEP and Tevatron, the bound on the lightest Higgs boson mass, loop-induced quantities like $(g-2)_\mu$ and $\mathrm{Br}(b \to s\gamma)$ and the constraints from WMAP on the cold dark matter density $\Omega_\chi h^2$ and other cosmological observations.

The different SUSY models that have been studied include:

1. Constrained Minimal Supersymmetric Standard Model (CMSSM): In this model, the universality of scalar masses, gaugino masses and trilinear parameters is assumed at the input GUT scale.

2. Non Universal Higgs Model (NUHM): In this model, the soft SUSY-breaking scale masses for the two Higgs doublets are not universal. As compared to the CMSSM, these are two additional parameters and, at low energies, may be taken to be the Higgs mixing parameter μ and the CP-odd Higgs boson mass, m_A.

3. Very Constrained Minimal Supersymmetric Standard Model (VCMSSM): This is a version of the CMSSM with additional relations between the soft tri- and bi-linear SUSY parameters: $A_0 = B_0 + m_0$.

4. Gravitino Dark-Matter Model (GDM): This is a model with a gravitino LSP so that the gravitino is the dark matter candidate. But this is done with an MSUGRA framework where the gravitino mass is taken to be equal to m_0 at the input GUT scale and again the soft tri- and bi-linear parameters are related by: $A_0 = B_0 + m_0$.

For the CMSSM, VCMSSM and GDM, it is found that $m_{1/2}$ is constrained to be of the order of a few 100 GeV and this suggests light sparticles observable at the LHC and ILC. On the other hand, m_0 values in NUHM could be considerably larger and make production of sparticles at ILC, at least at a centre-of-mass energy of 500 GeV, difficult.

One of the most promising channels for SUSY discovery at the ILC is $\tilde{\tau}$ pair production followed by the decay of the $\tilde{\tau}$ to a τ and the LSP. A work reported at the meeting [22] showed how the measurement of the polarisation of the τ in its one-prong hadronic decay channel will provide information on the underlying SUSY breaking mechanism as well as a determination of SUSY parameters. The process studied was: $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$ with $\tau_1 \to \tau\chi_1^0$. The normalised centre-of-mass angular distribution of the τ to a pion (or a vector meson) and a neutrino allows a determination of its polarisation P_τ. The composition of χ_1^0 determines the polarisation of the τ and it is this composition that yields model-discrimination. In MSUGRA: $P_\tau = +1$, in non-universal SUGRA: $P_\tau = \cos^2\theta_\tau - \sin^2\theta_\tau$, in models of anomaly mediation one gets $P_\tau = -1$, while in gauge mediation $P_\tau = \sin^2\theta_\tau - \cos^2\theta_\tau$. Thus it is possible to distinguish different SUSY models by measuring P_τ. The work also demonstrates how P_τ may be used in a global fit for a model-independent determination of SUSY parameters.

Another study presented [23] dealt with the implications for gaugino masses of renouncing the universality of gaugino masses at the GUT scale. In the framework of $SU(5)$ GUT, for example, such non-universality may result from the vacuum expectation value of the F-term of a chiral superfield which appears in the gauge-kinetic function.

In spite of being unequal, constraints on the neutralino and chargino masses result from the grand-unified framework. Upper bounds on neutralino masses and sum rules for neutralino-chargino mass relations are obtained. Not unexpectedly, these masses have significant dependence on the representation of the GUT group. These relations can be probed in the decays of neutralinos and higgs at the ILC.

In another presentation [24], the process $e^+e^- \to \tilde{t}_1\tilde{t}_1 \to c\chi_1^0 c\chi_1^0$ was studied in the case where the stop-neutralino mass difference is small. The scenario is motivated by SUSY Dark Matter studies where the dark matter precision determination is dependent on the scalar mass determination through the co-annihilation process. An Iterative Discriminant analysis method is used to weight each event in such a way as to optimize signal to background.

At a centre-of-mass energy of 260 GeV, for a 122 GeV stop and 107 GeV neutralino, 50 fb^{-1} luminosity and 50% efficiency 560 signal and 200 background events are estimated using the Iterative Discriminant analysis. This goes towards a precise determination of the stop mass and precise prediction for dark matter.

A proposal to look for dark matter at colliders was presented [25] in the context of a model where the gravitino is the lightest-supersymmetric particle (LSP) and the dark matter candidate and the next-to-lightest supersymmetric particle (NLSP) is a $\tilde{\tau}$ with lifetimes ranging from a few seconds to several years. This is studied by looking at the decay of the $\tilde{\tau}$ via $\tilde{\tau}_1 \to \tau\tilde{G}$. At the ILC, copious $\tilde{\tau}_1$ production yields a very precise determination of the $\tilde{\tau}$ parameters with results such as

$$\begin{aligned} \delta m_{\tilde{\tau}} &\sim 10^{-3} \\ \delta m_{\tilde{G}} &\sim 10^{-1} \end{aligned} \qquad (2)$$

The analysis can be extended to case where the NLSP is any of the other sleptons.

3. Extra Dimensions

One work presented [26] studied a low-scale supersymmetry-breaking scenario. SUSY-breaking in this model is mediated by low-scale gravity in a warped extra dimension. Due to the warping SUSY breaking scale Λ is brought down to the 1 – 10 TeV range. Hidden sector becomes visible due to strong interaction with the visible sector fields and production of hidden sector fields, X, at collider energies becomes possible. The production and decay of X at LHC and ILC has been studied and the phenomenology is very similar to radion phenomenology. A 1 TeV ILC should probe via $e^+e^- \rightarrow ZX$ masses of X $\sim\ 1.85$ TeV.

In another presentation [27], a model of universal extra dimension, where all the particles are free to propagate in a fifth dimension which is compactified on a S_1/Z_2 orbifold, was considered. Kaluza-Klein (KK) number conservation in the model yields a lightest KK particle (LKP) which is γ_1. The KK excitation of the electron E_1 has a mass equal to that of the γ_1 but the degeneracy is lifted by radiative corrections. In this work, the process $e^+e^- \rightarrow E_1^+E_1^-$ at the ILC energies is studied with $E_1 \rightarrow e\gamma_1$. This decay proceeds with a 100% BR. It is found that KK electrons give forward-peaked events due to t-channel dominance and this implies large forward-backward asymmetries which will be observed at the ILC. It is shown that it is possible to use angular distributions to obtain precise information on these KK states.

A paper which studied the modification of the standard Einstein-Hilbert action in models of TeV-scale gravity through the addition of higher curvature terms was also presented [28]. These are higher-dimensional terms which involve the curvature tensor and their introduction results in new ghost and scalar fields in D-dimensions. The ghost is removed from the spectrum by fine-tuning the model parameters but KK excitations of the scalar starting around a TeV in mass result and the phenomenology of these scalars is studied. It turns out that the KK excitations of the scalar has weak couplings in both the ADD and the RS models and does not alter the phenomenology in any serious fashion. On the other hand, the higher-curvature terms also modify the relationship between the fundamental scale in D dimensions and the Planck scale in 4 dimensions. This leads to a modification of the KK sectors of the ADD and the RS models and can lead to $O(1)$ modifications of the cross-sections for graviton emission or exchange in both models.

4. Interface with Cosmology

Another presentation [29] dealt with the issue of how to use the ILC to identify the dark matter particle and to infer dark matter properties from the measured particle spectrum and cross-sections in a Minimal Supersymmetric Standard Model study with 24 independent parameters. The scans of the 24-dimensional space was done using the Markov Chain Maotne Carlo Technique for 4 SUSY points (LCC1 – LCC4) of the LC/Cosmology study group. It was found that masses and splittings in typical examples have errors smaller by a factor of 3 – 10 compared to LHC errors. Also polarisation at ILC may help resolve multiple solution ambiguities prevalent at the LHC (bino-, wino-, higgsino-like LSP).

Rate of production of gamma rays in galactic halos is proportional to dark matter annihilation. Determination of the annihilation cross-section allows a model independent determination of dark matter density. The study concluded that a case for a 1 TeV ILC is very strong.

In yet another study [30], it was shown that dark matter annihilation into e^+e^- yields cosmic positron signals which can be probed in experiments like Pamela and AMS-2. If dark matter is detected in these experiments it will allow for mass determination in these experiments. The signal guarantees ILC will see $\gamma +$ DM pair production leading to spin and properties determination of dark matter at ILC.

5. Conclusions

In this paper, we have summarised the presentations made at the LCWS06 in Bangalore in the sessions on Beyond Standard Model Physics and Cosmological Connections. While significant progress has been made, there is still a lot of concentrated effort needed in pinpointing the role of the ILC in specific model contexts. No doubt much of this will be helped by the physics that the LHC will provide us with and the synergy and the complementarity of these two colliders has been the focus of several recent studies. Another theme of recent interest has been the interplay of collider signatures of new physics with cosmology. Clearly, there is a lot of interesting physics to look forward to in the coming decade.

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